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RECENT DEVELOPMENTS IN FIBER-REINFORCED ADDITIVE MANUFACTURING OF INJECTION MOLDING INSERTS

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INTRODUCTION

Digitization and industry 4.0 (I4.0) processes have increased the need and possibilities of smart, flexible, and cost efficient production. Focusing this development to the injection molding (IM) industry, IM inserts manufactured from additive manufacturing (AM) vat photopolymerization (VP) have been developed and increased their market share over the past years. [1]–[3] The inserts comprise the possibility of digital part development at low entry costs and therefore are a technology used for pilot production.

The authors conclude that challenges regarding the lifetime of polymer inserts in connection with the involvement of thermal stresses, crack propagation, and molding cycle time can be tackled by fiber-reinforced AM. Lifetime has been increased by a factor of 20 reaching an average lifetime of 4.500 shots and an increase the attractiveness of the inserts for prototyping and pilot production has been achieved. So far, short, virgin, and unseized carbon fibers (CFs) with diameters of $7.2\,\mu m$ and average lengths of $100\,\mu m$ as well as glass fibers (GFs) have been utilized in a number of investigations.

Considering the increased lifetime of the discussed inserts, further factors such as the molding cycle time increase in their significance for further developments. The tested molding configurations included a $1.5\,s$ mold closing and injection, $7\,s$ packing and cooling, $1.5\,s$ mold opening and ejection, followed by $10\,s$ natural cooling. Both packing and cooling, as well as natural cooling are characterized by longer times as required for competitive materials such as brass, aluminum, steel, and silicium carbide (SiC) and are tackled by the presented research.

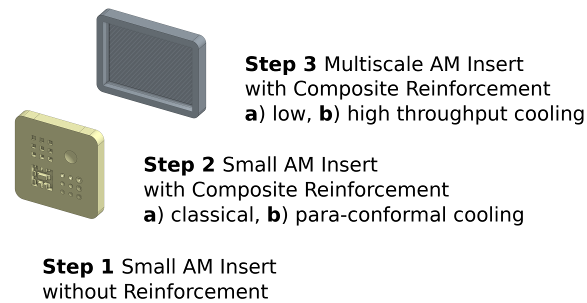

FIGURE 1. AM IM insert development steps considering fiber-reinforcement and cooling as crucial factor for an enlargement of the application space.

SYNTHESIS OF CURRENT CAPABILITIES

The authors have performed both experimental and numerical investigations to face the challenges described below facing moreover the challenge of effusivity of polymer insert material in an IM process.

Heat Transfer and Cooling Mechanisms

Numerical simulations as well as investigations using a thermographic camera were conducted in order to understand the modified cooling mechanisms of polymer inserts produced by VP. An understanding of both convectional as well as liquid cooling was achieved for multiple insert development steps shown in Figure 1. [4], [5]

The inserts were modeled with dimensions of $(20 \times 20 \times 2.7)\,mm^3$ (small inserts) and $(60 \times 80 \times 10)\,mm^3$ (multiscale inserts) including effusivity in relation to the thermal properties in comparison to the injected acrylonitrile butadiene styrene (ABS) material. The interface temperature was calcu-

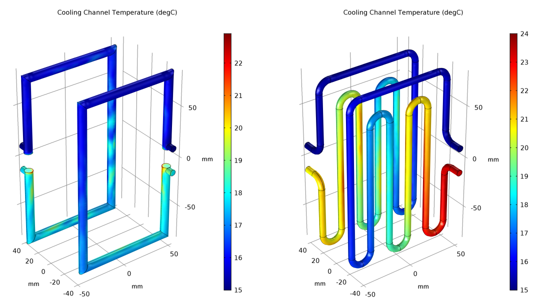

FIGURE 2. Temperature of conventional (left) and para-conformal (right) cooling channels at a throughput of $5\,\mathrm{L/min}$*. Doe to the improved flowability of the fluid in the channels with rounded corners, a higher throughput of up to* $10\,\mathrm{L/min}$ *is possible.*

lated as

$$T_i = \frac{b_1 T_1 + b_2 T_2}{b_1 + b_2}, \tag{1}$$

$$b_i = \sqrt{k_i \rho_i c_{p_i}}. \tag{2}$$

Whereas:

$$T_i = \text{temperature at interface}$$
$$k_i = \text{thermal conductivity}$$
$$\rho_i = \text{density}$$
$$c_{p_i} = \text{heat capacity}$$

This resulted in an interface temperature with ABS of $32.2\,°\mathrm{C}$ (steel), $121.0\,°\mathrm{C}$ (photopolymer), $30.0\,°\mathrm{C}$ (brass), and $27.4\,°\mathrm{C}$ (SiC) whereas a 4-fold difference between the photopolymer and the comparison materials can be noted and significantly influences the insert temperature. [4]

Investigations confirmed the crucial importance of advanced cooling mechanisms such as para-conformal cooling where the standardized mold geometry is modified by techniques available for conformal cooling providing a uniform surface temperature and therefore reducing thermal stresses. The amount of heat removed from the system by the cooling liquid has been increased from $2.9\,\mathrm{kW}$ to $5.7\,\mathrm{kW}$ after the change from conventional cooling to para-conformal cooling shown in Figure 2. This factor reaches significance as insert and part volumes increase while at the same time utilizing the freedom of design that comes with AM techniques.

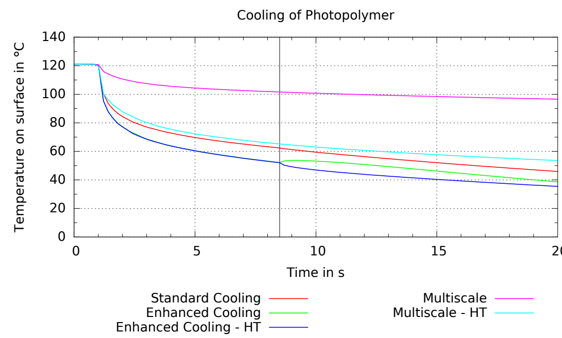

FIGURE 3. Surface temperature of small AM inserts with standard cooling, enhanced cooling, with and without high throughput (HT, $10\,\mathrm{L/min}$*), and multiscale inserts.*

By the use of enhanced cooling, the overall temperature of the insert was reduced (as shown in Figure 3), which allows a reduction of the natural cooling time by $6\,\mathrm{s}$ while starting the molding cycle at the same insert temperature. The use of larger insert geometries corresponds to longer cooling times, which can be reduced by an advanced cooling of the standardized steel mold in the background.

Fiber Orientation and Control

Conventional VP processes include a flat build plate in a bottom-up or top-down machine whereas the part is manufactured in layers at usual heights of lower 2-digit µm forcing the fibers into a layered orientation by removing one degree of freedom (DOF).

Simulations have been conducted predicting the final fiber orientation as a result of the fluid flow of the resin due to moving boundaries representing the build plate. Several potential solutions have been found to control the fiber orientation and increase the orientation angles out of the build plate orientation. [6]

Streamline analysis was performed according to [7]–[9] predicting the fiber orientation in bottom-up and top-down technologies including a modified build plate design. The usually horizontal alignment of fibers in bottom-up printing processes can be changed in top-down processes and isotropic fiber orientation can be achieved by a modified build plate with cylindrical, vertical holes shown in Figure 4.

Practical experiments at an open top-down machine have shown furthermore an improvement in warping of the free surface due to surface tension

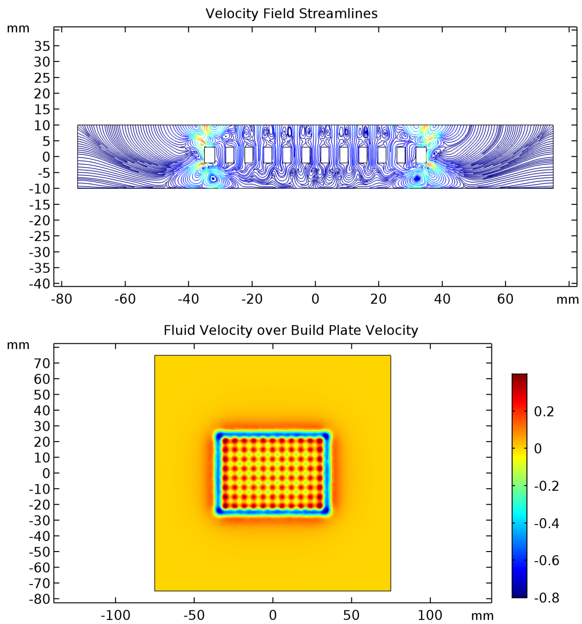

FIGURE 4. Streamlines as fiber orientation prediction (top) and vertical velocity factors normalized by the build plate velocity (bottom) for a modified geometry with vertical cylindrical holes in the build plate.

of the thermoset photopolymer resin when using modified build plates. Due to the suction effect of the moving build plate, a velocity is induced in the fluid, which again results in a warped surface. The waiting time for relaxation of the surface tension effect has been reduced by 50 % when using the modified build plate design. The results also allow the conclusion that fiber orientation in a thermoset photopolymer can be controlled by the orientation of the part in the resin vat.

FAILURE MECHANISMS

Cracks represent the biggest threat for insert lifetime and their understanding is crucial for a further enhancement of lifetime and product quality.

Fiber-Matrix Interface and Internal Defects

Investigations on thermal curing mechanisms of multi-component photopolymer resins have been conducted facing the low level of chemical bonding of CFs (and less GFs) to the curing polymer. It could be concluded that a combination of thermal and optical energy introduction during the printing process allows an improved fiber-matrix interface quantified by an increased strength and stiffness of the final part.

Visualized in Figure 5, it was possible to increase the specific load at break by a factor

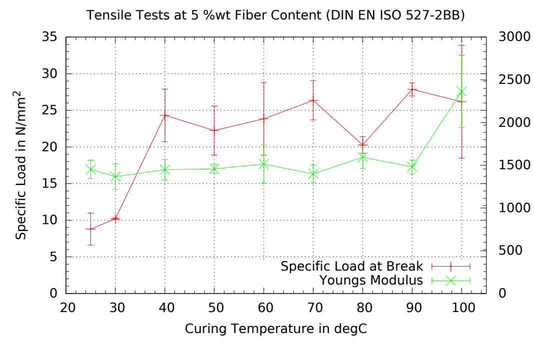

FIGURE 5. Tensile properties of a thermoset photopolymer with 5 $\%_{wt}$ glass fiber content at different curing temperatures utilizing both thermal and optical curing of the photopolymer.

of up to 3 at certain cases utilizing both optical as well as thermal curing of the thermoset photopolymer filled with 5 $\%_{wt}$ glass fiber. 50 % trimethylolpropane triacrylate containing 600 ppm monomethyl ether hydroquinone as inhibitor in combination with 50 % 2-Hydroxyethyl methacrylate containing 250 ppm monomethyl ether hydroquinone as inhibitor and 0.2 % Irgacure 819 (chemical name: Bis(2,4,6-trimethylbenzoyl)-phenylphosphineoxide) was utilized as thermoset photopolymer. Youngs modulus was improved at higher temperatures whereas a significant difference was measured at 80 °C following investigations presented in [10] concluding a gelation of the thermoset photopolymer at higher temperatures.

Other weakening factors such as air intrusions have been investigated using X-ray computed tomography (CT) whereas a significant potential for improvement has been identified, which can be realized by reducing the air intrusion during both the mixture and the manufacturing process. Potential solutions under investigation are a modified stirring mechanism as well as a vacuum mixture, which is already in use e.g. for cold-molding of probes for scanning electron microscopy (SEM). [11]

Crack Propagation and Fiber Alignment

It could be shown by the use of SEM, CT, and optical microscopy analysis that two types of cracks can be identified: (1) smaller surface cracks propagating over the heated surface in a random orientation perpendicular to the surface; and (2) deep cracks penetrating the insert up to 1.8 mm, oriented in parallel to the printed layers (if existing, and therefore also in parallel to the fiber orientation) and finally leading to a total failure of the part. Examples are given in Figure 6 showing both randomly oriented surface cracks as well as penetrating cracks oriented along the printed layer and therefore the fibers. [11], [12]

X-ray tomography was conducted using a ”ZEISS XRadia 410 Versa” device at an operation voltage of $40\,\mathrm{kV}$ and a power of $10\,\mathrm{W}$ using low energy 1 (LE1) filter and a macro objective (LFOV) or a 4X objective. A resolution of $2\,\mu\mathrm{m}$ was obtained as highest resolution. Prior investigations on the fiber orientation during a layer-wise manufacturing process in a bottom-up machine were confirmed using an elliptic approximation of the resolved fibers following the method presented in [13]. [11] A tensor estimation for one of three sample regions is shown in Figure 7 for fiber orientation outside of the printing plane. Orientation along the printed plane is randomly distributed.

Surface cracks have a limited influence on the surface quality of the final product if the injection pressure is reduced and the representation of the surface is limited. Otherwise, the importance of surface quality needs to be considered in the context of an internal prototyping process. Surface roughness was concluded to be stable at an average of $R_a = 0.45$ µm.

It could be shown that fibers have a significant influence on the crack propagation which is reduced to $1.25\,\%$ as compared to a non-reinforced polymer. The concluded crack orientation and dimensions lead to the understanding that an isotropic fiber orientation should be achieved for further development of AM IM inserts since the material deals both with periodical mechanical and thermal stresses during the process.

Life Cycle and Environmental Factors

A full life cycle assessment (LCA) has been conducted investigating the influence of CFs on the environmental impact of IM inserts in comparison to conventional materials such as brass, steel, and aluminum under the consideration of contributions by [14]–[17]. The improved lifetime plays an important role in the reduction of the investigated factors of global warming potential (GWP) and human toxicity (HT). Both AM and computer numerical control (CNC) machining were investigated in a comparison assessment which did not include the injection molding process itself since the process is identical for both process chains. The boundaries are shown in Figure 8 including

FIGURE 6. Deep cracks aligned along the printed layers and propagated due to the corner effect of thermal and mechanical stresses (top) and randomly oriented surface cracks (middle) with a higher density on the right side of the image due to the orientation of the material injection from the right. Individually identified fibers in an overview (bottom).

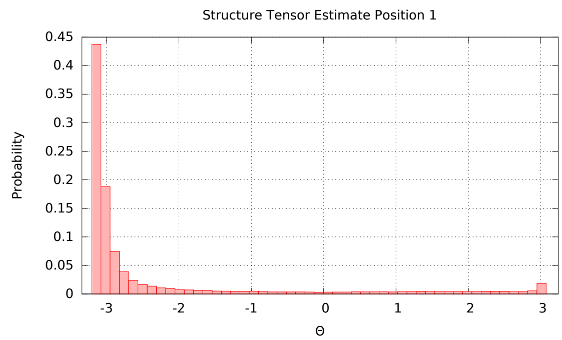

FIGURE 7. Structure tensor estimation outside the printing layers. Due to geometrical restrictions in a bottom-up printing process, only a slight angle between the printed plane and the fiber is possible.

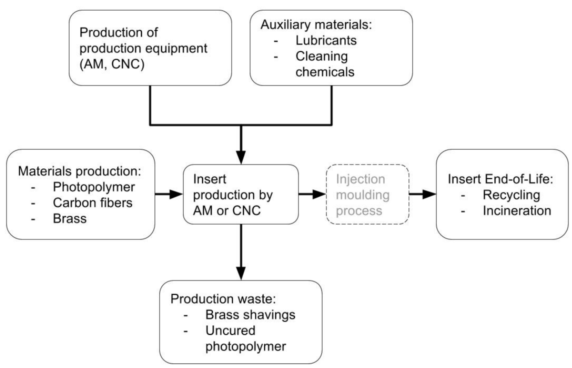

FIGURE 8. System boundaries of the conducted LCA with exemption of the IM process itself.

the influencing factors such as materials used in the production process and waste generation.

The LCA showed a huge potential of production optimization in such a way that the amount of wasted resin is reduced therefore especially reducing the HT level. Moreover, there are currently no sustainable end of life (EoL) scenarios available. [18]

CONCLUSION

While industrial applications slowly start their appearance on the market for non-fiber-reinforced IM inserts, fiber-reinforcement has shown to bring further improvement to the material. With an overall understanding of the crack propagation mechanisms in correlation to the fiber orientation as well as a predictive description of flow mechanisms in the resin vat, a determined fiber orientation can be achieved helping to further improve the mechanical and thermal properties of the inserts. These properties play an important role in parameters for further industrial production when directly influencing the molding cycle time. Since the natural cooling time has been reduced by over $50\,\%$ and LCA showed a significant reaction on the lifetime of the inserts, they can be considered a sustainable method for future production in a smart, digital fabrication environment.

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